Cryptographic protocol analysis– A short introduction to the Scyther tool

P. Kotzanikolaou

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Outline

1. Introduction to Cryptographic protocols
2. State spaces in security protocol analysis
3. Scyther: A short introduction

Content

What is a Cryptographic protocol?

- **Cryptographic protocol**: A formal definition of **actions** (computations) and **message exchanges** (communications) between some entities, in order to achieve some claimed **security properties**.
- Example of claimed security properties:
  - entity authentication
  - key agreement
  - aliveness, etc.
- Crypto protocols usually combine other **cryptographic primitives** (e.g. encryption schemes, signature schemes etc).

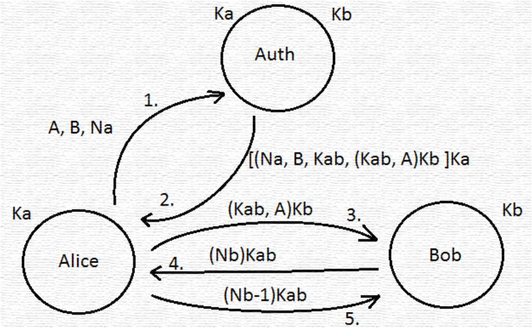
Example: The Needham-Schroeder (N-S) protocols

Two protocols by N-S.

- The Symmetric-Key N-S Protocol:
  - Entities: Two users (Alice, Bob) and a trusted authentication server Auth.
  - Uses symmetric keys shared between each user and Auth (K_a, K_b).
  - Protocol Goal (claimed security property): establish a fresh session key between two parties (K_{ab}) over an insecure network. The session key is secret from all others.
- The Public-Key N-S Protocol:
  - Entities: Two users (Alice, Bob) and a trusted authentication server (Auth).
  - Uses a public-key pair for each entity $((PK_a, SK_a), (PK_b, SK_b), (PK_{Auth}, SK_{Auth}))$.
  - Protocol Goal (claimed security property): establish a secret session key between two parties (K_{ab}) over an insecure network.

N-S symmetric protocol: Description

Figure: Graphical example of Needham Schroeder protocol



What is Wrong with N-S?

- Crypto protocols are error-prone. Crypto protocols require **formal security analysis**.
- The N-S protocol was found **flawed** using an automatic tool (Casper/FDR) *17 years later*!
- Vulnerable to **replay attack**: Attacker uses older, compromised value for K_{ab} and then replays $\{K_{ab}, A\}_{K_b}$ to Bob, who is unable to tell that the key is not fresh.
- Flaw was *not detected in the original proof* due to **different assumptions** on the intruder model.

Using Tools for Crypto Protocol Analysis

- **Automatic tools** based on formal analysis have been presented in the literature.
- Main problem: Security in cryptographic protocols is **undecidable**.
- Tools address undecidability in different ways:
  - By restricting the protocol behaviors explored using **roles**.
  - By using **abstraction methods**.

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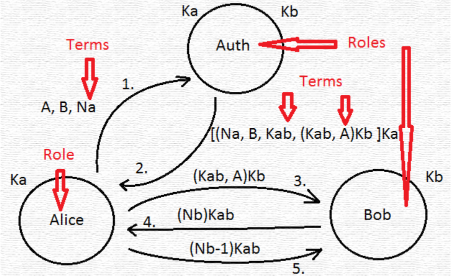
Symbolic analysis

- Symbolic analysis models:
  - Possible behavior of *legitimate agents* executing a security protocol.
  - Possible behavior of *active intruders*.
- A **security protocol** is defined as a finite set of communicating processes, referred to as "**roles**".
  - Roles names can be Client/Server or Initiator/Responder.
- Protocols define exchange of **message terms** between **roles**.

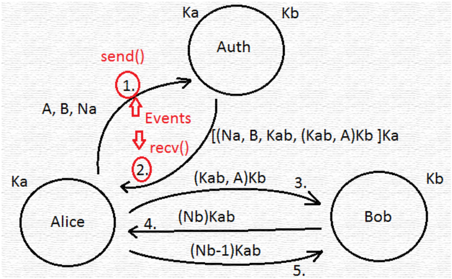
Figure: Roles and Terms in N-S example



Symbolic analysis

- A protocol specifies the **behavior** of a number of roles.
  - A mapping from **role names** to **processes**.
  - A role consists of a sequence of **send and receive events**.
- **Process P** defines a **possibly infinite** number of behaviors.
- Each **behavior** is represented as sequences of **events**.
- A **sequence of events** is referred to as a **trace** of the system.
- All behaviors of a process P denoted by set of traces $tr(P)$.

Figure: Roles and Terms in N-S example



Symbolic analysis

- Roles are executed by **Agents**.
  - Each role can be executed **any number of times** by unbounded number of agents.
- Protocol Q with $|dom(Q)| = n$ roles, $dom(Q) = r_1, r_2, ..., r_n$
  - $Q(r)(a_1, ..., a_n)$ the process that is the instantiation of the role r, where r_1 is substituted by a_1 etc.
- For any protocol Q, the behavior of the agents is defined by the process:

$$\|_{x \in dom(Q)} !Q(x)(\_, ..., \_)$$

Symbolic analysis

- Notation _, interpreted as the **unspecified choice**.
  - $Q(Resp)(\_, \_)$ denotes a single execution of the responder role, with any choice for the agent names.
- $X \parallel Y$ denotes the process consisting of the **parallel composition** of the process X and Y .
- $!X$ denotes the **replication** of the process X, i.e. $!X = X \parallel (!X)$.

Cryptographic protocol analysis

- **Verifying** security properties of protocols $\approx$ checking whether **all possible behaviors** satisfy **desired security properties**.
- Given a protocol Q, the system describing the behavior of the agents in the context of the intruder is defined as:

$$Sys(Q) = Intruder \ ||| \, |||_{x \in dom(Q)} !Q(x)(\_, ..., \_)$$

- *If there exists an attack on (a trace property of) a protocol Q, it is represented in the set of traces of the system $Sys(Q)$.*
- *If no trace in $tr(Sys(Q))$ exhibits an attack, there is no attack on the protocol.*

Cryptographic protocol analysis

- Crypto protocol analysis tools usually apply some **restrictions**.
  - Do not explore all elements from the set $tr(Sys(Q))$.
  - Protocols are not actually verified in the full system Sys but rather **in a subset of the behaviors**.
  - Subsets can be defined by using a **Scenario**.
- A **Scenario** is a multi-set of processes.
  - S: the set of *all possible* scenarios
  - S_c: the *subset* of concrete scenarios in which **no unspecified agents** (**_**) occur.

State spaces in security protocol analysis

- $Sys(Q)$ contains any number of replications of each role
- $MaxRuns(Q, m)$ system contains only a finite number of replications of each role.
- Let Q be a protocol and let m be an non-negative integer. Then:

$$MaxRuns(Q, m) = Intruder \; ||| \; |||_{i=1}^{m} \left(\sum_{x \in dom(Q)} Q(x)(\_, .., \_) \right)$$

State spaces in security protocol analysis: Example

- Using a **single honest agent** a and **single compromised agent** e, for a protocol with roles $r1, r2$, $tr(MaxRuns(Q,1))$ is equal to:

$$(\cup_{k\in a,e} tr(Scen(r_1(a,k)))) \cup (\cup_{k\in a,e} tr(Scen(r_2(k,a))))$$

- This yields a set of four scenarios.

Practical implications

Two possible results of state space analysis:

1. Finding attacks on a protocol
   - If an attack is found, unexplored parts are of little interest.
2. No attack was found.
   - If no attack is found, then we only have **some assurance** of the correctness of the protocol.
   - State space choices have great impact on analysis results.
   - Scenarios that do not cover all possibilities may result to erroneous output.
   - Even for two honest agents, the simplest protocols already need **42 concrete scenarios** to explore exactly all attacks involving two runs.

Tools for automated analysis of security protocols

Most tools are free and open source. Some examples are:

- **Avispa** (Automated Validation of Internet Security Protocols)
- **ProVerif**
- **Casper/FDR**
- **Scyther**

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Scyther tool

- Tool by Cas Cremers for the automatic verification of security protocols.
- Can be found at: `http://users.ox.ac.uk/~coml0529/scyther/`
- Python based. Current version is 1.1.3.
- Available for various platforms (Linux, Windows, Mac OS).
- Installation instruction are included in the downloadable Scyther archives.

...Scyther tool

- Verifies protocols with unbounded number of sessions.
- Can characterize protocols, yielding a finite representation of all possible protocol behaviors.
- Not required to provide scenarios for property verification, all possible protocol behaviors are explored by default.
- Core elements in a Scyther input file are protocol definitions.
- Has been used to:
  - **analyse** IKEv1, IKEv2 protocol suites and ISO/IEC 9798 family along with a large amount of Authenticated Key Exchange (AKE) protocols.
  - **find** new multi-protocol **attacks** on many existing protocols.

Scyther tool - Variables and values

- Scyther manipulates **terms**.
- **Atomic terms** can be any identifier, usually string of alphanumeric characters.
  - **Constants**
  - **Freshly generated values**: random values, declared inside roles using the fresh declaration.
  - **Variables**: Agents can use variables to **store received terms**.
- Atomic terms can be combined into complex terms.
  - (x,y) : pair of terms x and y.
  - It is allowed to write n-tuples.

Scyther tool - Encryption

- Any term can act as a key for **symmetrical encryption**.
- Encryption of ni with a term kir is written as: $\{\ ni\ \}kir$
  - Unless kir **explicitly defined** as part of asymmetric key pair, this is interpreted as symmetric encryption.
- **Symmetric-key infrastructure** predefined: $k(X, Y)$ denotes long-term symmetric key shared between X and Y.
- **Public-key infrastructure (PKI)** is predefined: $sk(X)$ denotes the long-term private key of X and $pk(X)$ the corresponding public key.
- **Example**: Nonce of the initiator (ni) encrypted with initiator public key: $\{\ ni\ \}pk(I)$

Scyther tool - Events

- **recv** and **send**: Receiving and sending a message, respectively. Each send event will have a corresponding recv event.
- **Claim events**: Used in role specifications to model intended security properties.
  - **Secret**: This claim requires secrecy for a given parameter term.
  - **SKR**: Equivalent to the Secret claim. Additionally mark the parameter term as a session-key. Consequence is that using session-key reveal adversary rule will now reveal the parameter term.
  - **Alive**: Aliveness (of all roles).
  - **Weakagree**: Weak agreement (of all roles).
- **Example**: Claim event models that Ni is meant to be **secret**. $claim(I, Secret, Ni);$

Demo time

We will explore two examples (both included in the protocol examples of the Scyther tool):

- The symmetric-key N-S protocol.
- The public-key version of the N-S protocol.

References

- Cremers, Cas JF, Pascal Lafourcade, and Philippe Nadeau. "Comparing State Spaces in Automatic Security Protocol Analysis." Formal to Practical Security 5458 (2009): 70-94.
- Cremers, C. J. F. Scyther: Unbounded Verification of Security Protocols. ETH, Department of Computer Science, 2007.